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Title: Kiwi-TNT Simulation Model

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Kiwi-TNT Simulation Model

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NEN-2

Advanced Nuclear Technology

LANL

The Kiwi-TNT Test (Toonerville Trolley)

January 12, 1965

Control Drum Speed: 4000 deg/s

Maximum Excess Reactivity: 8.3$

Spike Yield: greater than 3E+20 fissions

“the heat vaporized some of the graphite, resulting in a colorful explosion that sent fuel elements flying through the air”

Objective of Research

- ***Inadvertent Criticality & Number of Fissions Method Development and Analysis Support***
- "LANL will develop a defensible methodology for establishing the maximum number of fissions for postulated inadvertent criticality events. The methodology may include several methods, such as hand calculations, sophisticated modeling, and the use of historical data."
- Historical test, Kiwi TNT, posed a starting point for predictive simulations to determine the number of fissions and excursion understanding.
- This presentation gives results of that effort.

Excursion Modeling

- The Thesis
  - The ultimate reactivity quench mechanism is core disassembly via ejection of core material through coolant passages.
- The Simulation Model - Coupled Neutronic/Hydrodynamic Method
  - Point-Reactor Kinetics Model
  - Carbon Equation of State (EOS)
  - Energy Equation
  - Continuity Equations
  - Fluid Mechanics
  - 1-D (Radial) Discretization into i zones

Point-Reactor Kinetics Model

$$\frac{dP}{dt} = \frac{\beta}{\Lambda}\left[(R-1)P + \sum_i f_i D_i - RS\right]$$

$$f_i = \frac{\beta_i}{\beta}$$

$$\frac{dD_i}{dt} = \lambda_i(P - D_i)$$

$$R = R_{in} + RS + \alpha_T \sum_i I_i(T_i - T_o) + \alpha_\rho \sum_i I_i(\rho_i - \rho_o)$$

$$p = p_o P = \sum_i s f_i p_o P = \sum_i p_i$$

Reactivity Feedback (Core Density)

- One-Group Perturbation Theory

$$\Delta\rho = \frac{\int \left(\nu\delta\Sigma_f - \delta\Sigma_a\right)\phi^2 dV}{\int \nu\Sigma_f \phi^2 dV}$$

- Core density change reactivity effect

$$\Delta\mathrm{R} = \alpha_\rho \frac{\int (\rho - \rho_o)\phi^2 dV}{\int \phi^2 dV} = \alpha_\rho \sum_i I_i(\rho_i - \rho_o)$$

- Importance Factors

$$I_i = \frac{\phi_i^2 V_i}{\sum_i \phi_i^2 V_i}$$

Time Evolution

- Probability of not initiating sustained chain prior to time t
  - $P_{NI}(t) = e^{-\int_0^t (k(t')-k_p)Sdt'}$

$$= e^{-\int_{t_{prompt}}^{t_{max}} \left(\frac{dk}{dt}t'\right)Sdt'} \; e^{-\int_{t_{max}}^{t} (k(t_{max})-k_p)Sdt'}$$

$$= e^{-\left(\frac{dk}{dt}(t_{max}-t_{prompt})^2\right)S/2} \; e^{-(k(t_{max})-k_p)S(t-t_{max})}$$

Define: $t - t_{max} = t_{wait} = 37\, ms$

$P_{NI} = 0.44 = 44\%$

- Excursion Time
  - $t_{excursion} = t_{insertion} + t_{wait} + t_{peak}$
  - $t_{excursion} = 45\, ms + 37\, ms + 33\, ms = 115\, ms$

Carbon EOS

Triple Point = 4530 K

Sublimation line:

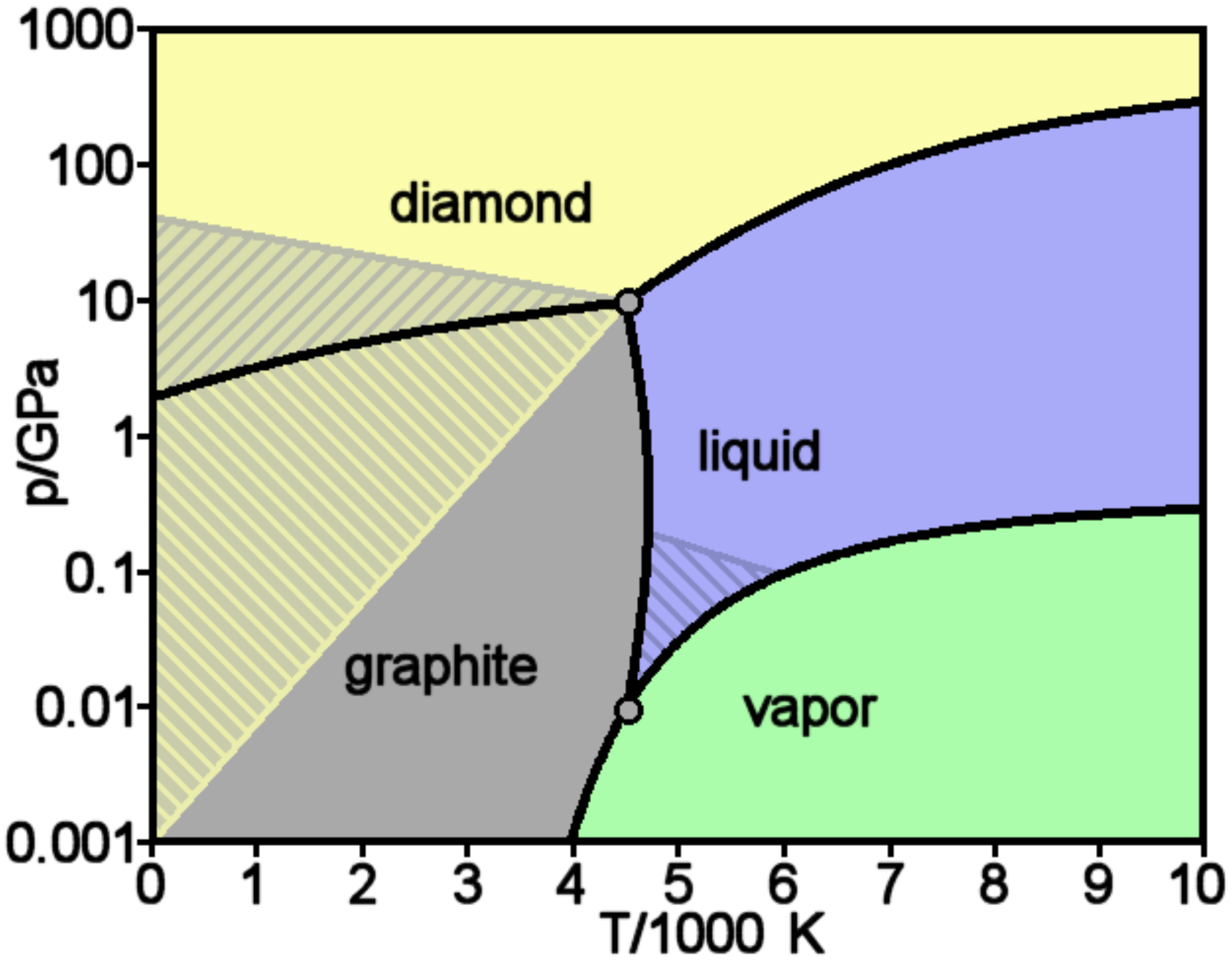
*P=(1.3E+17) * exp(-1.09E+05/T)*

Clausius-Clapeyron Relationship:

$$\frac{dP}{dT} = \frac{P h_{fg}}{T^2 R_{gc}}$$

Heat of Sublimation:

$$h_{fg} = (1.09E + 5)R_{gc}$$
$$= 75.5\ MJ/kg$$



Energy Equation

- Below 1 atm (sensible heating)
$$\rho_i V_i C_{pi} \frac{dT_i}{dt} = p_i$$

- Above 1 atm and below the triple point
$$\rho_i V_i C_{pi} \frac{dT_i}{dt} = p_i - w_{vi} h_{fg}$$

- At the triple point (melting)
$$\Gamma_i = (p_i - w_{vi} h_{fg})/h_f$$

Continuity Equations

- Vapor

$$w_{vi} = u_i \rho_{vei} A_i$$

- Liquid

$$\frac{dm_{li}}{dt} = \Gamma_i - \frac{m_{li}}{\tau} \qquad (\tau \text{ is a residence time})$$

- Core Density

$$\frac{d\rho_i}{dt} = \left(-w_{vi} - \frac{m_{li}}{\tau}\right) / V_i$$

Fluid Mechanics - Vapor

- Bernoulli's Principle (Compressible Flow)

$$h_i = \frac{u_i^2}{2} + h_{ei}$$

$$\frac{T_{ei}}{T_i} = \frac{2}{k+1}$$

$$\frac{\rho_{vei}}{\rho_{vi}} = \left(\frac{2}{k+1}\right)^{\frac{1}{k-1}}$$

$$u_i = \sqrt{2kR_{gc}T_{ei}}$$

- Vapor Jet Power

$$P_{vji} = w_{vi}\,\frac{u_i^2}{2}$$

Fluid Mechanics - Liquid

- Liquid “packet” acceleration (Impulse Principle)

$$\Delta m_{li}\frac{du_{li}}{dt} = w_{vi}(u_i - u_{li})$$

- Estimating τ , time to travel mean path

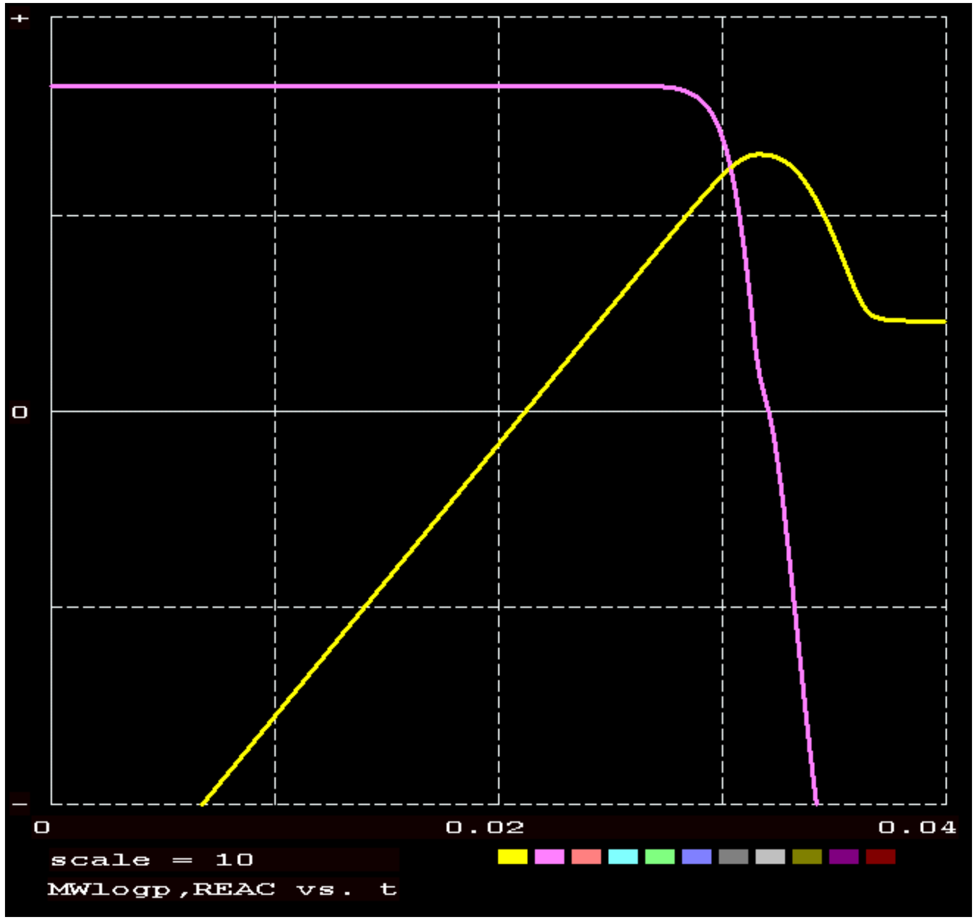
$$l_{mp} = \int_0^{\tau} u_{li}dt$$

- Power required to move packets

$$p_{lji} = w_{vi}u_{li}(u_i - u_{li})$$

Simulation Results

Reactivity →



← log(Power)

Simulation Results

- Peak Power: 6.3E+06 MW
- Spike Yield: 5.9E+20 fissions
- Pulse Duration: 0.0028 s
- Fraction of Core Vaporized/Melted: 27%
- Vapor Exit Temperature: 3775 K
- Vapor Exit Velocity: 2706 m/s
- Vapor Jet Power: 3.4E+03 MW

Summary

- Kiwi-TNT simulation model developed and tested
- Core density reactivity coefficient, core importance factors, and power distribution shape factors calculated using MCNP6.2
- Initiation probability model tested
- Carbon EOS and physical properties investigated
- Vapor transport based on Bernoulli's Principle
- Phenomenological liquid transport model developed
- Simulation results indicate "colorful explosion"
- Future work involves ***Inadvertent Criticality Release Fractions Determination and Analysis Support***